Magnetoconductance noise and irreversibilities in submicron wires of spin-glass n^+-$Cd_{1-x}Mn_xTe$

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Signatures of spin-glass freezing such as the appearance of $1/f$ conductance noise, the recovery of universal conductance fluctuations, aging, as well as magnetic and thermal irreversibilities are detected in mesoscopic wires of $Cd_{1-x}Mn_xTe$:I at millikelvin temperatures. Spectral characteristics of conductance time series are consistent with the droplet model of short-range spin-glasses.

PACS numbers: 73.50 Td, 72.15.Rn, 73.61.Ga, 75.50.Lk

Since the seminal suggestion of Altshuler and Spivak [1] and of Feng *et al.* [2] that the sensitivity of quantum interference of scattered electron waves to the instantaneous configuration of the localized spins in mesoscopic systems might serve as an important tool for testing models of spin glasses [3], considerable efforts have been made to fabricate and study metallic nanostructures doped with magnetic impurities. In particular, Israeloff *et al.* [4] detected $1/f$ conductance noise in $Cu_{1-x}Mn_x$ at temperatures above 5 K. A detailed analysis of those data by Weissman and co-workers [5] has demonstrated the magnetic origin of the noise at and below the freezing temperature T_g as well as a satisfactory agreement of its magnitude with the Feng *et al.* [2] theory. Moreover, the results were shown [5] to point to the hierarchical model of the spin-glass phase [6], a conclusion drawn from the character of non-gaussian behavior of the conductance time series in mesoscopic wires of $Cu_{0.91}Mn_{0.09}$.

After this initial progress, *no* mesoscopic signatures of spin freezing were found by both Van Haesendonck *et al.* [7] and Benoit *et al.* [8]. This was attributed to a reduction of the strength of the Ruderman-Kittel-Kasuya-Yosida (RKKY) interactions by disorder inherent to nanostructured samples and to a corresponding increase of the role of the Kondo effect [9]. It has been also pointed out that the total number of the localized spins in the studied structures might be too small for the phase transformation to show up [8]. By contrast, a rather robust spin freezing was observed by de Vegvar and co-workers [10] in nanostructures of Cu:Mn. In particular, an antisymmetric term in the magnetoresistance tensor, generated by the frozen spins [11], persisted above T_g characteristic for the bulk material. This surprising observation, together with a visible reduction of the Kondo resistivity, were taken as indicative of importance of magnetic inclusions, such as MnO [12].

We report here on a study of the resistance noise and magnetic field-induced fluctuations in submicron wires of a diluted magnetic semiconductor (DMS) [13] $Cd_{1-x}Mn_xTe$:I with electron densities greater than that corresponding to the metal-insulator transition. In DMS, the localized spins are coupled by short-range antiferromagnetic superexchange interactions, which in the studied range of Mn concentrations, $0.07 \le x \le 0.2$, lead to the spin-glass transition at $0.3 \lesssim T_g \lesssim 2.2$ K [14], respectively. Owing to a large difference between the relevant length scales, the studied wires are mesoscopic from the point of view of the electronic properties but macroscopic as far as the range of magnetic interactions is concerned. This feature, together with the absence of the competing Kondo effect (due to the ferromagnetic character of the *s*-*d* exchange interaction [13]), make DMS particularly suitable for the meaningful examination of the spin-glass phase by the phenomena of coherent transport. Our results corroborate the existence of $1/f$ magnetic noise, detected here down to 30 mK. At the same time, we observe other signatures of the spin-glass freezing such as aging, thermal and magnetic irreversibilities as well as a strong increase in the amplitude of both UCF and the noise when the temperature *and* the magnetic field are reduced below the freezing line. We demonstrate that the present data are consistent with the droplet model [15] of short-range spin-glasses as well as with qualitative predictions of Monte Carlo simulations of conductance in Edwards-Anderson spin glasses [16].

According to the theoretical model of mesoscopic phenomena [1,2,17,18], out of eight contributions to var(ΔG), seven are diminished by the electron interaction with the Heisenberg spins virtually independently of spin dynamics, while the remaining term varies in tact with the changes of the local spin configurations. As a results, the spins act as phase breakers at time scales shorter than the time constant of the resistance meter, while they are a source of equilibrium conductance noise or irreversibilities at longer epochs. In particular, the Fourier power spectrum $S(f)$ of the stationary noise is proportional to the Fourier transform of the normalized spin-spin autocorrelation function $C(f) = 2\chi''(f,T)/\pi f\chi(T)$ [2,18]. Particularly interesting is the case when the noise is controlled by a small number of fluctuators so that the conductance time series may exhibit deviations from gaussian statistics. Spectral characteristics of these deviations, the so-called second spectrum $S_2(f)$ [5,19,20], is white when the fluctuators act independently but assumes a nonwhite character for either interacting fluctuators [5] or dynamic redistribution of

the current between its possible paths [21]. Thus, $S_2(f)$ may provide information on whether glassy dynamics reflect wandering of spin configurations between local free energy minima (hierarchical dynamics) or rather a spontaneous formation and annihilation of compact droplet excitations [5].

Our $Cd_{1-x}Mn_xTe$:I films with $x = 0.07$ and 0.20 ± 0.005, having thickness of 0.3 μm, and electron concentrations n of about 2×10^{18} cm^{-3} were grown by MBE on SI GaAs with 10 Å ZnTe and 3 μm CdTe undoped buffer layers. The magnitudes of n and x were determined from the room temperature Hall data and the spectral position of the photoluminescence line, respectively. It has been confirmed in course of this work that the electrical activity of iodine impurities [22], in stark contrast to indium donors used previously [23], varies little with x for $x \leq 0.3$. Accordingly, the highest values of n, which we obtain by iodine doping is—in the case of $Cd_{0.8}Mn_{0.2}Te$—by four orders of magnitude greater than that which could be reached with indium doping. The wires were fabricated by means of electron-beam lithography, followed by wet etching in 0.05% solution of Br_2 in ethylene glycol. As shown in the inset to Fig. 1, they have a mean width of $W = 0.3$ μm, and the arrangement of the contacts suitable for five-probe measurements of conductance noise $G(t)$ by the a.c. method [24]. In order to avoid electron heating [25], current intensity as low as 100 pA was employed, which limited the studied range of $1/f$ noise to $f \leq 1$ Hz. The output filters served as an anti-alias device, and they were set to reject the output voltage components of frequency greater than $f = 0.3$ and 3 Hz in the case of measurements *vs.* H and t, respectively. A typical field sweep rate was $dH/dt = 0.5$ kOe/min, and ten 12 bit data points were acquired per second. The Kaiser and square windows were employed for the determination of the first and second Fourier power spectra, respectively.

Figures 1 and 2 present the conductance $G(H,t)$ in the wires with $x = 0.07$ and 0.2, respectively. Similarly to previously studied paramagnetic $Cd_{0.99}Mn_{0.01}Te$:In [23], in the present case the electron transport is found to be significantly affected by the giant and temperature dependent spin-splitting of the conduction band [13]. In particular, the spin-splitting leads to the weak-field positive magnetoresistance [26], visible as a dip near $H = 0$ in Figs. 1(a) and 2(a). At the same time, the redistribution of the electrons between the spin subbands, and the associated changes in the length of the interfering waves of the carriers at the Fermi level, appears to constitute the dominant mechanism of UCF generation in any magnetic material [23]. The latter accounts for a monotonic shift with temperature of the field values corresponding to given conductance features, an effect clearly seen in Fig. 1(a). Below, we shall focus, however, on those phenomena which are specific to the spin-glass phase.

Starting with the data for n^+-$Cd_{0.93}Mn_{0.07}Te$ wire (Fig. 1), we note that the UCF amplitude rms(ΔG), in low magnetic fields and at $T > 0.3$ K is weakly temperature dependent and smaller than that found in similar wires of n^+-$Cd_{1-x}Mn_xTe$, $x \leq 0.01$ [23]. However, rms(ΔG) is seen to increase abruptly below 0.3 K, temperature corresponding to T_g in the bulk material with $x = 0.07$. In the same temperature range, a dramatic increase in the conductance noise is observed. Our findings reveal, therefore, a destructive effect of the fluctuating spins on the UCF, and the appearance of the low frequency noise when the spin dynamics become slow, corroborating qualitatively expectations of theoretical models [2,18] and numerical simulations [16].

As shown in Fig. 2, particularly strong and complex signatures of the spin-glass freezing are found in the case of n^+-$Cd_{0.8}Mn_{0.2}Te$ wire. Such a sensitivity of the conductance to spin configurations in the whole temperature range below 1 K stems from a large value of $T_g \approx 2.2$ K in this material. Additionally, relatively large chemical and spin disorder for $x = 0.2$ brings the electron liquid close to the localization boundary and, thus, makes it particularly sensitive to local variations in the scattering potential. Some relevant examples of history-dependent effects are depicted in Fig. 2(a), which shows a series of magneto-fingerprints, measured in succession as a function of the magnetic field (and time) after a heat pulse and subsequent cooling from $T > T_g$ to $T \approx 0.02T_g$. The effect of aging, that is, a gradual decrease in both the fluctuation amplitude and the differences between subsequent traces is clearly visible. Magnetic irreversibilities persist even after long waiting time. Together with low frequency equilibrium noise, they make the correlation coefficient to be as low as 0.7 for the two most lately registered traces of Fig. 2(a). According to spectral densities $S(f)$ presented in Figs. 3(a) and 3(b), the noise is white at $T > T_g$. Below T_g, however, $S(f)$ is seen to assume the form $1/f^{1+\gamma}$, where at 50 mK and in $H = 0$, $\gamma = 0.3$ and 0.5 for $x = 0.07$ and 0.2, respectively.

An important aspect of our data is that they provide information on how the magnetic field affects the spin-glass dynamics. It may appear that the field will reduce fluctuations of the Mn spins and, thus, will result in an increase of the UCF amplitude. Indeed, such an increase has been found by others [8] and by us in the paramagnetic phase. At $T < T_g$, however, rms(ΔG) of both the UCF [Figs. 1(c) and 2(c)] and noise [Fig. 2(b)] is observed to *decrease* when the magnetic field gets stronger. The former demonstrates an increase of integrated $S(f)$ in the frequency range $f \geq 0.3$ Hz, while the latter its decrease for $f \leq 3$ Hz. At the same time, according to results on $S(f)$ at 50 mK presented in Figs. 3(a) and 3(b), γ decreases from 0.3 and 0.5 in $H = 0$ to 0.1 and 0.2 in 36 kOe, for $x = 0.07$ and 0.2, respectively. This means that the maximum of $\chi''(f)$ shifts in the magnetic field to the range of frequencies greater than those explored in the present experiment. Thus, our findings lead con-

sistently to the conclusion that the principal effect of the magnetic field on spin-glass freezing is to displace the spectral weight of the magnetic excitations toward higher frequencies.

As we have already noted, of particularly relevance is the analysis of non-gaussian effects in noise statistics. In the case of the wire with $x = 0.07$, the normalized variance of $S(f)$ for seventy successively collected data trains, and average over four octave bands of f, is $s_2 = 1.1 \pm 0.2$ at 50 mK. For the adopted normalization, this indicates that the noise is essentially gaussian, a conclusion corroborated by the frequency dependence of correlation between the amplitude and phase components of the Fourier transform of $G^2(t)$, *i.e.*, $s_f^{(2,a)}$ and $s_f^{(2,\phi)}$ [20], the latter depicted in Fig. 3(c).

In contrast to the data for $x = 0.07$, a stronger freezing specific to $x = 0.2$, together with the proximity of the metal-to-insulator transition, result in significant non-gaussian effects. In particular, the value $s_2 = 16 \pm 2$ at 100 mK [Fig. 2(d)], indicates that only a few fluctuators controls the noise over the studied frequency range [5]. It turns out that non-gaussian statistics result from phase correlation, so that $s_f^{(2,\phi)}$ is plotted in Fig. 3(c). Of particular significance is its week frequency dependence, $s_f^{(2,\phi)} \sim f^{-0.3}$. Actually, despite an expected contribution of the dynamic current redistribution in the vicinity of the localization threshold [21], the frequency dependence of $s_f^{(2)}$ in $Cd_{0.8}Mn_{0.2}Te$ is *weaker* than in metallic $Cu_{0.91}Mn_{0.09}$ [5], as shown in Fig. 3(d). This important observation implies that the noise in DMS is dominated by a set of independent fluctuators, presumably, droplet-like excitations. The comparison of those two material systems provides, therefore, the experimental indication that the droplet model [15] describes slow dynamics more accurately in the case of the short range superexchange interaction than when the coupling between the spins proceeds *via* the long range RKKY mechanism.

In summary, our results demonstrate that on the scale of the coherence length of the electron wave function in DMS, the magnetic subsystem remains unperturbed by the growth or nanostructuring process. This has made possible to observe, by means of quantum phenomena, effects of the temperature and the magnetic field on equilibrium and non-equilibrium glassy dynamics, providing the important verification of the theoretical predictions [1,2,18] and of the numerical simulations [16]. In view of our findings, the absence of both the conductance noise [7,8,10] and the field-induced irreversibilities [10] in mesoscopic metallic spin-glasses might indeed result from finite-size and clustering effects. Statistical analysis of the conductance time series indicates that in contrast to diluted magnetic metals [5], DMS constitute the material system, to which the description of spin-glass properties in terms of droplet excitations [15] may directly apply. Our results demonstrate also that the magnetic field shifts gradually the spectral weight of these excitations toward higher frequencies.

We thank J. Chroboczek and J. Kossut for discussions, and KBN for support under Grant No. 2-P03B-6411.

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FIG. 1. Conductance G as a function of the magnetic field H (a) and time at $H = 0$ (b) in the wire of n^+-$Cd_{0.93}Mn_{0.07}Te$ at selected temperatures down to 30 mK (uppermost traces). Note that G decreases in the upward direction. Inset to (b) shows atomic force micrograph of the sample. Temperature dependencies of the root mean square conductance fluctuations for $x = 0$, 0.01 [23], and 0.07 (empty symbols) and noise for $x = 0.07$ (full symbols) are shown in (c); solid lines are guide for the eye. Arrow marks the bulk value of the spin-glass freezing temperature for $x = 0.07$.

FIG. 2. Conductance G as a function of the magnetic field (a) and time (b) in the wire of n^+-$Cd_{0.8}Mn_{0.2}Te$ at 50 mK. The traces in (a) were taken in succession starting from the uppermost, and are shifted by $1e^2/h$ for clarity. Arrows indicate directions of the sweep. Note that G decreases in the upward direction. Temperature dependencies of the root mean square conductance fluctuations (empty symbols) and noise (full symbols) are shown in (c), while fractional variance of the noise power spectrum in (d); solid lines are guide for the eye.

FIG. 3. Fourier power spectra of noise, $S(f)$ in the wires of $Cd_{0.93}Mn_{0.07}Te$ (a) and $Cd_{0.8}Mn_{0.2}Te$ (b) at selected temperatures and magnetic fields. Normalized second noise spectra $s_f^{(2,\phi)}$ taken in the bandwidth from 0.1 to 0.6 Hz at 50 mK are compared in (c) to expectations for the gaussian $1/f$ noise [20]. The frequency dependence of $s_f^{(2)}$ (normalizing to and subtracting the gaussian expectation) is shown in (d) for $Cd_{0.8}Mn_{0.2}Te$ at 50 mK and $Cu_{0.91}Mn_{0.09}$ at 11 K [5]. Lines in (a) and (b) show $1/f^{1+\gamma}$ dependence, while in (c) and (d), except for the gaussian background, are guide for the eye.